IRRIGATION MANAGEMENT EFFECTS ON NITRATE LEACHING AND MOWING REQUIREMENTS OF TALL FESCUE

by

JOSHUA D. CHABON

B.S., Kansas State University, 2006

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Horticulture, Forestry and Recreation Resources
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2014

Approved by:

Co-Major Professor
Dale J. Bremer

Approved by:

Co-Major Professor
Jack D. Fry

Abstract

Irrigation management may influence nitrate leaching under tall fescue (*Festuca arundinacea*) and also affect its mowing requirements. Two experiments were conducted on tall fescue growing on a Chase silt loam soil near Manhattan, Kansas. Each experiment was arranged in a split-plot design, with irrigation treatments applied to whole plots: 1) frequency-based irrigation, water was applied three times weekly to deliver a total of 19 mm water wk^{-1} regardless of weather conditions; and 2) soil moisture sensor (SMS)–based irrigation, 34 mm of water was applied when soil dried to a predetermined threshold. In the first experiment, sub-plots consisted of unfertilized turf, and N applied as urea or polymer-coated urea at 122 and 244 kg ha^{-1} yr^{-1}. Suction lysimeters at a 0.76 m depth were used to extract nitrate leachate bi-monthly. Turf quality was rated weekly. In the second experiment, subplots were mown at 5.1 cm or 8.9 cm, based upon the 1/3 rule, with or without monthly applications of the growth regulator trinexapac-ethyl (TE). Data were collected on total mowings and visual turf quality. Soil moisture sensor-based irrigation resulted in water savings of 32 to 70% compared to frequency-based irrigation. Leaching levels did not exceed 0.6 mg L^{-1} and no differences in leaching were observed between irrigation treatments or among N sources. All fertilized turf had acceptable quality throughout the study. In the second experiment, irrigation strategy did not influence total number of mowings. In the first year, TE application reduced total mowings by 3 in tall fescue mowed at 5.1 cm, but only by 1.5 when mowed at 8.9 cm. In the second year, mowing at 8.9 vs. 5.1 cm or using TE vs. not resulted in a 9% reduction in total mowings each. The SMS-based irrigation saved significant amounts of water applied compared to frequency-based irrigation, while maintaining acceptable quality, but irrigation treatments did not affect nitrate leaching or

mowing frequency in tall fescue on fine silt-loam soil. Nitrate leaching, regardless of amount, was well below the standards set for human health (10 mg L^{-1}). Applications of TE are more beneficial for turfgrass mowed at lower cutting heights.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to acknowledge my advisors, Dr. Dale Bremer and Dr. Jack Fry. I would never have achieved this without their guidance and tutelage. I would also like to thank them for their patience and support during the writing process as life threw many curveballs at me and my family.

I would like to thank the other members of my committee, Dr. Steve Keeley and Dr. Cathie Lavis. A special thanks to Dr. Lavis for her assistance with numerous irrigation issues that arose throughout the study.

I need to also thank the other graduate students during my stay: Dr. Tony Goldsby, Dr. Kenton Peterson, Dr. Cole Thompson, Zane Raudenbush and Ross Braun. I had many questions during my time here and their support was invaluable. A special thank you to Dr. Tony Goldsby, for assisting me with installing and updating the irrigation system to make this research possible. Another special thank you to Dr. Kenton Peterson for the immense amount of help he provided in statistical analysis.

I would like to acknowledge Dr. Kathy Lowe in the Kansas State Soil Testing Lab for analyzing my leachate samples.

Finally, I need to thank my wife, Stephanie, for putting up with my dream and helping me realize it.

Dedication

To my wife and daughter;
Stephanie and Baylee

Chapter 1 - Irrigation Management and Fertilization Effects on Water Application Amounts and Nitrate Leaching in Turfgrass

Abstract

Urbanization in the US has increased the area covered with turf, causing greater concern about water amounts used for irrigation and the potential for leaching from nitrogen (N) fertilization in urban watersheds. My objectives were to evaluate differences in water applied and nitrate leaching among irrigation and N-fertilization treatments. The two-year study was conducted on a Chase silt loam soil near Manhattan, Kansas. Treatments of traditional frequency-based and soil moisture sensor (SMS)-based irrigation were assigned to whole plots of tall fescue [*Festuca arundinacea*] turfgrass. Frequency irrigation cycles ran three times weekly to apply 19 mm water wk^{-1} and SMS cycles applied 34 mm of water when soils dried to a predetermined threshold. Subplot treatments consisted of N applications of urea and polymer-coated urea, each to provide N at 122 and 244 kg ha^{-1} yr^{-1}, and no N (control). Suction lysimeters were used to extract nitrate leachate every two months. Visual quality of turf was rated weekly. The SMS-based irrigation applied 32 to 70% less water than frequency-based irrigation. No differences in nitrate leaching occurred between irrigation treatments or among N sources and levels did not exceed 0.6 mg L^{-1}. All fertilized turf had acceptable quality throughout the study. Results indicate SMS-based irrigation saves water compared to frequency-based irrigation while providing acceptable quality, and nitrate leaching is negligible under the conditions of this study.

Introduction

Sources of potable water are dwindling as the global population rises. Rapid urbanization has led to an increase in the area covered with turfgrass (Morris, 2003) and, consequently, in the amounts of water used for its irrigation. The total area of turfgrass is estimated to cover 16 to 20 million hectares in the U.S., which is an area three times larger than any other irrigated crop (U.S. Department of Agriculture [USDA], 2004, 2006; Milesi et al., 2005).

In the U.S., 50% to as much as 80% of the turfgrass is in residential landscapes (Grounds Maintenance, 1996; USDA, 2004, 2006). A recent survey of residential homeowners found that those with in-ground irrigation systems watered more frequently and routinely than homeowners without in-ground systems (Bremer et al., 2012). Those authors also reported that 16 to 24% of homeowners with in-ground irrigation systems never adjusted their controllers. Improperly adjusted in-ground irrigation systems can deliver a much higher amount of water than manually operated sprinklers, on a per area basis (Mayer et al., 1999; Vickers, 2001). Factors like irrigation amount, frequency and rate can affect the potential for nitrate leaching, such as over-irrigation on turfgrass (Barton and Colmer, 2006).

A number of studies have linked declining water quality to urbanization (Hamilton et al., 2004; King and Balogh, 2001). Increased concentrations of nutrients and pesticides associated with lawn care are among the many factors linked to declining surface and ground water quality (Petrovic and Easton, 2005). The regular inputs of irrigation and fertilizer required by turfgrass have often caused it to be viewed as a source of N leaching (Barton and Colmer, 2006).

Nitrogen is essential for plant survival and maintenance of quality and thus, is typically applied in any industry involving plant life, including home lawns. Consequently, various chemical forms of N are watched closely in drinking water supplies because they can be detrimental to human health. Nitrates (NO_3^-) in drinking water above 10 mg L^{-1} (ppm) can affect a blood cell's ability to carry oxygen and thus, may cause trouble with breathing and blue-baby syndrome (methemoglobinemia) (Chand et al., 2011; EPA, 2012). High levels of nitrates also may lead to eutrophication in surface water reservoirs, causing them to become non-potable (Smith, 1998).

Leaching of N below turf may be highly influenced by soil texture, fertilizer source, rate and timing of applications, and irrigation/rainfall amounts (Petrovic, 1990; Snyder et al., 1984). Establishment of turfgrass via seeding in areas containing no existing turfgrass creates the highest risk for leaching, most notably in coarse textured soils (Easton and Petrovic, 2004; Erickson et al., 2010; Geron et al., 1993). Newly sodded turf is also more prone to leaching than established swards on coarse soils in Florida (Trenholm et al., 2013). If N is over-applied, there is the potential for leaching in established turfgrass stands, especially in sandy soils. However, leaching can be greatly reduced with proper management of fertilization and irrigation practices (Carey et al., 2012).

Nitrogen leaching may be significantly less under turfgrass than other landscape species. For example, St. Augustinegrass [*Stenotophrum secundatum* (Walter) Kuntze] that received N at 300 kg N ha^{-1} yr^{-1} on a coarse textured soil leached only 4.1 kg N ha^{-1} yr^{-1} compared to a mixed species stand of trees, shrubs, and ornamental ground covers that received only 150 kg N ha^{-1} yr^{-1} but leached 48.3 kg ha^{-1} yr^{-1} (Erickson et al., 2001). In another study, only 1% of N applied to St. Augustinegrass on a sandy soil was leached over a period of 12 months compared to 33% of applied N that was leached in a mixed-species stand on a sandy soil (Cisar et al., 2003).

Fertilizer rates and types, as well as irrigation management, can also impact N leaching. In 'Tifgreen' bermudagrass [*Cynodon dactylon* (L.) Pers.] grown on Pompano fine sand in Florida, daily irrigation and fertilizing with 600 kg N ha yr^{-1} resulted in greater leaching (81 mg L^{-1}) when fertilized with ammonium nitrate than with a slow-release sulfur-coated urea N (14 mg L^{-1}) (Snyder et al., 1984). In the latter study, peak leaching was less overall when irrigation was controlled by soil moisture sensors (SMS) compared to daily (frequency-based) irrigation, but leaching remained greater in plots fertilized with ammonium nitrate (30.8 mg L^{-1}) than with sulfur-coated urea (8.4 mg L^{-1}). In tall fescue grown on Hanford fine sandy loam and fertilized at a rate of 390 kg N ha^{-1} yr^{-1}, leaching was also greater during winter months when fertilized with ammonium nitrate than with slow-release N sources (Wu et al., 2010). Thus, when fertilized at similar rates, slow-release fertilizers may reduce leaching compared to water-soluble fertilizer sources (Barton and Colmer, 2006; Engelsjord and Singh, 1997; Snyder et al., 1984). It also may be possible to reduce leaching rates of water-soluble fertilizers by adjusting the rate and timing of water applications or by applying less N more frequently (Engelsjord and Singh, 1997; Snyder et al., 1984). However, this can become more cost and time intensive.

Advances in irrigation technology have improved SMS so that, when properly installed and calibrated, they will accurately measure the soil water content within a given area. Attaching SMS to a controller results in a "smart" controller, which simply refers to the system's ability to adjust irrigation amounts and frequency based on soil moisture; other types of smart controllers include those based on local evapotranspiration and rainfall. In SMS-based smart controllers, SMSs can be assigned to individual or multiple irrigation zones. Typically, the controller will display soil water content as a percentage for each SMS. Through observation of the occurrence of wilt and the corresponding soil water content displayed by the controller, a threshold level can then be set for the SMS. This threshold can be set to trigger on at any level of visual drought stress, or a value higher than the level at which drought stress occurs, to maintain a desired turfgrass or plant quality. As soil water content drops below this threshold, the controller will trigger an irrigation cycle, or bypass irrigation altogether if soil water content remains above the threshold. Proper installation of SMS is important, because their placement in a non-representative (overly dry or wet) area may result in over- or under-application of water to the general area of turfgrass (Dukes, 2012). For example, installing SMS in a very low area of turfgrass that remains wet may cause surrounding drier areas to rarely or never receive irrigation, which could lead to plant death.

Smart controllers with properly calibrated SMSs have demonstrably improved irrigation efficiency and saved water on turfgrasses growing on coarse-textured soils (Cardenas-Lailhacar and Dukes, 2012). For example, in common bermudagrass in Florida, SMS systems saved up to 88% of the water applied with systems equipped with only a rain shutoff sensor, with no differences in turfgrass quality (Cardenas-Lailhacar et al., 2008). Those authors also reported that irrigation with SMS saved 72% of the water applied compared to traditional frequency-based controllers during wet conditions. An Australian study showed that SMS-based systems applied 25% less water than traditional frequency-based irrigation, and also reduced the amount of nitrate leaching in bermudagrass grown on sandy soils (Pathan et al., 2007). Aside from the two studies by Pathan et al. (2007) and Snyder et al. (1984), very little information is available about the interaction between SMS-based irrigation and leaching rates, particularly among different soil types, climates, and turfgrass species.

Researchers cited above who investigated leaching under SMS irrigation conducted their research on coarse soils; the effects of SMS irrigation on N leaching has not been investigated on finer soil types. Similarly, little research has been conducted with regards to the potential water savings with SMS on non-sand-based soils. Therefore, the objectives of this research were to evaluate differences between frequency-based irrigation and SMS-based irrigation in: (1) total amount of water applied; (2) nitrate leaching levels among various fertilizer rates and types; and (3) turfgrass quality.

Materials and Methods

This field study was conducted in 2012 and 2013 at the Rocky Ford Turfgrass Research Center near Manhattan, Kansas (39^{o}13’53” N, 96^{o}34’51” W). Soil type was a Chase silt loam (fine, montmorillonitic, mesic, Aquic, Argiudoll). An on-site, automated weather station recorded weather variables including rainfall.

Beginning in May, 2012, irrigation treatments were applied to six whole plots of tall fescue [*Festuca arundinacea*] that had been established for eight to nine months; whole plots measured 27.4 m by 9.1 m each. Whole plots contained five subplots that measured 1.2 m by 2.0 m. Turfgrass was mowed weekly at a height of 7.6 cm. Each zone consisted of eight total rotary irrigation heads. Four were set on the sides of each whole plot at 180 degree rotation and the remaining four were in the corners at a 90 degree rotation. All irrigation heads were Hunter I-20’s (Hunter Industries, San Marcos, CA, USA). Irrigation treatments began on 28 May and ended on 15 October in 2012 and began on 27 May and ended on 14 October in 2013.

In three of the six whole plots, irrigation was controlled by SMS attached to an automated controller (Acclima SC6, Acclima, Inc., Meridian, ID, USA). One SMS (digital time domain transmissometry, Model ACC-SEN-TDT, Acclima) was installed in each of the three whole plots managed by this controller. Each SMS was installed outside of the subplots and buried at a depth of 7.0 cm. Following the manufacturer’s protocol, “field capacity” was determined for each sensor as a percentage by volume (Acclima, 2007). This was accomplished by soaking the soil surrounding each SMS with water late in the evening, and waiting overnight to allow excess water to move through the soil profile. The next morning, a percentage by volume soil water content value was recorded for each SMS. Obtaining this “field capacity” reading allowed us to proceed with calculating a stress threshold for each SMS.

Irrigation audits were performed in 2011 and 2013 to evaluate net irrigation rates and distribution uniformity (Table 1.1) using standards by the Irrigation Association (Irrigation Association (IA), Falls Church, VA, USA). The initial audit was performed in 2011 prior to the study to calibrate the updates made to the irrigation system for this study. Distribution uniformity is a ratio that represents how uniformly the system applies water to the area; it should not be considered a measure of efficiency (Burt et al., 1997). The net precipitation rates in 2011 for frequency-based whole plots ranged from 25.9 to 30.2 mm hr^{-1}, and generally declined slightly to a range of 21.8 to 28.2 mm hr^{-1} by 2013. The net precipitation rate in 2011 for SMS whole plots ranged from 26.7 to 28.2 mm hr^{-1} and declined to a range of 22.4 to 25.4 mm hr^{-1} by 2013. The distribution uniformity in 2011 for frequency-based whole plots ranged from 0.69 to 0.79 and declined to a range of 0.54 to 0.59 by 2013. The distribution uniformity in 2011 for SMS whole plots ranged from 0.61 to 0.70 and declined to a range of 0.53 to 0.58 by 2013. Human (e.g., walking or driving over irrigation heads) and environmental (e.g., freeze/thaw of soils surrounding irrigation heads) factors can affect net irrigation rates and distribution uniformity over time, resulting in increases or decreases in their respective values.

Stress thresholds for the turfgrass were then determined for each sensor zone (Table 1.2). Three separate cycles of irrigation and dry-down were conducted, and the occurrence of drought stress was observed during each cycle. For these tests, drought stress was defined as the changing of turfgrass color and visual indications of wilt. The percentage soil water content corresponding to stress was recorded, and the average of all three observations was used as the threshold for each zone controlled by a SMS. These thresholds determined when irrigation was triggered in SMS irrigation treatments. Due to lower quality ratings in SMS irrigation plots than in frequency-based plots during some periods of 2012, thresholds were increased in all three SMS plots to reduce stress occurrence and improve quality ratings in 2013.

Irrigation in frequency-based irrigation plots was controlled by a Hunter Pro-C controller (Hunter Industries, San Marcos, CA, USA). The frequency-based irrigation treatments were set to automatically run three times weekly in 15 minute cycles. At this frequency, these whole plots received 19.4 to 22.7 mm of water per week in 2012 (2011 audit, Table 1.1) and 16.4 to 21.2 mm of water per week in 2013 (2013 audit, Table 1.1). This was designed to mimic typical irrigation scheduling of homeowners based on observations by the author after five years of experience in the lawn care industry.

Treatments

Experimental design was a split-plot with irrigation treatment as the whole plot factor and fertilizer treatment as the subplot factor. Irrigation treatments, which were replicated three times, included 1) frequency-based irrigation schedule of a "typical" homeowner that applied water as described earlier; and 2) SMS-based irrigation which was triggered when soil water content reached a predetermined threshold. In the SMS treatment, thresholds were determined as described earlier. When soil moisture dropped below the threshold, the system applied enough water to insure that all areas of the plots received at least 25.4 mm of water. All turfgrass plots were level and had full sun exposure. Irrigation treatments were applied from May to October in 2012 and 2013.

Suction lysimeters (Model 1900L, SoilMoisture Equipment Corporation, Santa Barbara, CA, USA) (Fig. 1.1) were installed so that the porous ceramic cup at the base was at a depth of 0.76 meters and centered in each subplot. Nitrogen treatments were randomly assigned to subplots within each whole plot (Table 1.3). Subplot treatments consisted of no N fertilizer (control), urea (46N-0P-0K), and polymer-coated urea (41N-0P-0K), each at 122 and 244 kg N ha^{-1} yr^{-1} (2.5 and 5.0 lbs 1000 ft^{-2} yr^{-1}). Extractions of soil solution from lysimeters were performed every two months during the growing season within each respective year. To perform these extractions, a vacuum was applied to each lysimeter at -50 cb for a period of 24 to 48 hours; more time was required when soils were dry. Soil solution was taken from the lysimeter using a syringe and injected into test tubes for sampling. Samples were kept in an ice water bath while in transit to the lab, to prevent the breakdown of nitrates (NO_3^-). Leachate samples were then analyzed for NO_3^- levels (Soil Testing Laboratory, Kansas State University).

Turfgrass quality was rated weekly on a scale of 1 to 9, on which 1 = brown, dormant or dead turfgrass, and a rating of 9 = optimum color, density, and uniformity (Skogley and Sawyer, 1992). A rating of 5 was considered the minimum acceptable turfgrass quality for a home lawn. Weekly quality ratings were averaged for each month.

Data were subjected to analysis of variance using PROC GLIMMIX in Statistical Analysis System (SAS Institute Inc., Cary, NC, USA), and means were separated using Fisher's Protected LSD at $P < 0.05$.

Results and Discussion

Water Savings

In 2012, a relatively dry year, SMS-based irrigation resulted in application of 32% less water than traditional frequency-based irrigation (Table 1.4). Much of the rainfall in 2012 occurred in June and August, in two large storm events (Fig. 1.2). In 2013, a relatively wet year, SMS-based irrigation resulted in 70% less water applied than frequency-based irrigation. Greater water savings during wet conditions with SMS irrigation was also reported when used on bermudagrass on sandy soils in Florida (Cardenas-Lailhacar et al., 2008, 2010). During wet conditions, soil moisture is maintained at higher levels, which allows the SMS system to bypass irrigation cycles more often than during dry conditions. In my study, this resulted in greater water savings between SMS and frequency-based irrigation in 2013 than in 2012.

Between years, 50% less water was applied by irrigation in 2013 than in 2012 in SMS plots, primarily because more precipitation was received in 2013 (Fig. 1.2). Higher air temperatures in 2012 also probably contributed to greater water use by the turfgrass and faster drying of soils from April through August in 2012 compared with 2013 (Fig. 1.3). This 50% reduction occurred after accounting for an additional 14% less water applied due to a loss in efficiency in the irrigation systems in SMS plots as shown by the irrigation audits. We also observed a reduction of 8% by irrigation in 2013 than in 2012 in frequency-based plots (Table 1.4). This reduction was likely caused by periods of maintenance to the irrigation system in 2013, when it was not running during its regular schedule. This 8% reduction occurred after accounting for 11% less water applied due to the loss in efficiency in the irrigation systems in frequency-based plots as shown by the irrigation audits.

Cardenas-Lailhacar et al. (2010) compared SMS-based to frequency-based irrigation treatments on sandy soils in Florida, and found that SMS-based irrigation applied 8 to 56% less water during a dry year. In another study, also on sandy Florida soils, SMS-based irrigation saved 54 to 88% of the water applied by frequency-based irrigation with a rain sensor, and 62 to 92% of the water applied by frequency-based irrigation without a rain sensor, during a wet year (Cardenas-Lailhacar et al., 2008). In an arid Australian climate on sandy soils, SMS-based treatments saved 27% of the water applied with frequency-based irrigation over a growing season (Pathan et al., 2007). Haley and Dukes (2012) found that SMS-based irrigation in residential lawns saved 65% water, even if homeowners were allowed to interact with their systems. All of the previous studies were conducted on bermudagrass.

In St. Augustinegrass, SMS-based irrigation resulted in application of 11 to 53% less water than traditional, frequency-based irrigation treatments on sandy soils in Florida (McCready et al., 2009). Results from the studies described above reveal that SMS-based irrigation saved water compared to frequency-based irrigation on sandy soils, whether in Florida or in Australia, and regardless of the turfgrass species or the different climates represented by the two regions. The water savings that resulted by using SMS-based systems on tall fescue in my Kansas study on silt loam soils were similar to the water savings in those studies, which indicates SMS-based irrigation can save water across multiple soil types, climates, and turfgrass species.

Nitrate Leaching

Nitrate leaching across treatments ranged from 0 to 0.577 mg L^{-1} in 2012 (Table 1.5) and from 0 to 0.190 mg L^{-1} in 2013 (Table 1.6). These nitrate levels were considerably lower than the EPA's 10 mg L^{-1} threshold.

In my study, there were also no differences in leaching between SMS- and frequency-based irrigation, despite SMS plots receiving significantly less water (Tables 1.4, 1.5, 1.6). This is in contrast to research by others in sandy soils, which has indicated reduced leaching with SMS-based irrigation. For example, in arid temperate Australia, nitrate leaching was 1.1% of the total applied N (0.83 kg N ha^{-1}) in frequency-based irrigation and only 0.3% of the total applied N (0.22 kg N ha^{-1}) in SMS-based irrigation (Pathan et al., 2007). Those authors attributed reduced leaching to consistently less soil water content present in the SMS-based plots, which resulted in less water moving through the soil profile. In 'Tifgreen' bermudagrass grown on fine sand and fertilized with ammonium nitrate at a rate of 600 kg N ha yr^{-1}, average leaching rates were 3.2 to 18.5 mg L^{-1} using frequency (daily) irrigation and 3.2 to 14.1 mg L^{-1} using SMS-based irrigation (Snyder et al., 1984). In the same study, sulfur-coated urea applied at the same rate leached an average of 1.4 to 6.4 mg L^{-1} using frequency irrigation compared to only 0.8 to 3.9 mg L^{-1} using SMS irrigation. It is likely that less water application by SMS irrigation results in reduced nitrate leaching in turfgrass stands, especially on coarser textured soils where rapid water drainage can be an issue.

The various fertilizer rates and types used in this study had no impact on nitrate leaching. Nitrate leaching in all N treatments was not different from the control that received no fertilizer. The fine-textured silt loam at the research site undoubtedly contributed to low leaching rates. Silt loam soils have relatively small pores, which retain water better and reduce drainage rates into the deeper profile. Miltner et al. (1996) performed a 3-year study on Kentucky bluegrass fertilized with N at 196 kg ha^{-1} yr^{-1} on a Marlette fine sandy loam, and found that nitrate leaching was typically below 1 mg L^{-1}. Frank et al. (2006) performed a 10-year study on Kentucky bluegrass on a Marlette fine sandy loam and fertilized with N at 98 and 245 kg ha^{-1} yr^{-1}. Of the 36 sampling dates in that study, nitrate leaching at the low N fertility rate was less than 5 mg L^{-1} on 26 sampling dates, while at the high N fertility rate nitrate leaching was greater than 20 mg L^{-1} on 20 sampling dates.

In contrast to my study, a number of studies on sandy soils reported much higher leaching rates. Snyder et al. (1984) reported average leaching rates of 3.2 to 18.5 mg L^{-1} for ammonium nitrate fertilizer compared to only 1.0 to 6.4 mg L^{-1} for a slow-release sulfur coated urea on ‘Tifgreen’ bermudagrass grown on fine sand and fertilized at a rate of 600 kg N ha yr^{-1}. In that study, nitrate levels exceeded acceptable EPA standards when a water-soluble N source (ammonium nitrate) was used, but not after slow-release (polymer-coated) fertilizer was applied. The combination of a high fertility rate, water soluble N source, and fine sand soils all contributed to higher nitrate leaching levels when using ammonium nitrate.

Maintenance of healthy turfgrass stands also tends to reduce nitrate leaching (Branham, 2008). The deep, extensive, fibrous root systems established by tall fescue (Su et al., 2008) such as in my study probably contributed to minimal leaching rates. In tall fescue grown on a fine sandy loam and fertilized as high as 390 kg N ha^{-1}, leaching never exceeded 7 mg L^{-1} even when fertilized with ammonium nitrate (Wu et al., 2010). In that study, however, leaching was lower when tall fescue was fertilized with poly-coated urea. Although the health of turfgrass stands as well as turfgrass species may affect leaching (Trenholm et al., 2012), soil composition likely plays a larger role in nitrate leaching (Branham, 2008; Mangiafico and Guillard, 2006; Miltner et al., 1996; Pathan et al., 2007).

In contrast to my results, Starrett et al. (1995) observed increased nitrate leaching when Kentucky bluegrass (*Poa pratensis L.*) growing on a fine loam in columns in the greenhouse received deep, infrequent irrigation vs. light, frequent irrigation following application of soluble N. The authors proposed that higher nitrate leaching may have been attributed to water movement through channels created by earthworms. However, the results found by Starrett et al. (1995) show that proper irrigation based on soil characteristics and fertility for the site can minimize the potential for nitrate leaching in turfgrass, which has been demonstrated by a number of studies (Miltner et al., 1996; Morton et al., 1988; Starr and DeRoo, 1981).

Results from my study on tall fescue growing on a silt loam soil indicate that nitrate leaching under fertilized turf will be the same as unfertilized turf whether using SMS- or frequency-based irrigation. In finer textured soils such as the silt loam herein, nutrients will not move through the soil profile as easily during irrigation events as in sandy soils. Not surprisingly, the contrasting results between my study and other studies that indicated significant reductions in leaching using SMS compared to frequency-based irrigation, suggests coarser textured soils will benefit more from the use of SMS irrigation in terms of reducing nitrate leaching (Snyder et al., 1984; Pathan et al., 2007).

Guertal and Howe (2012) investigated leaching in hybrid bermudagrass on three soils with three N sources, and reported nitrate leaching rates below 10 mg N L^{-1} once the grasses were established, including on sandy soils. However, irrigation was not a treatment in their study. Given the substantial differences in water applications between SMS and traditional frequency irrigation practices, as reported in this and other studies, it would be useful to compare leaching between SMS and frequency irrigation among different soil types, including with the use of different N sources.

Turf Quality

In July 2012, the visual quality of tall fescue receiving no fertilizer (control) within the SMS-based irrigation treatment fell below acceptable quality (Table 1.7). In August, and to a lesser extent in November, 2012, higher turf quality was sometimes observed in the frequency-based irrigation treatment than in the SMS-based treatment. This was likely caused by stress thresholds being set too low in the SMS-based irrigation treatments in 2012, which was corrected in 2013. Consequently, visual quality never dropped below acceptable in either irrigation treatment in 2013 (Table 1.8). A significant interaction was observed between irrigation and fertilizer in August and November in 2012 (Table 1.7), and in June and July in 2013 (Table 1.8). During these periods, tall fescue visual quality was typically highest in treatments receiving higher N levels and lowest in the control receiving no fertilizer.

Conclusions

Soil moisture sensor controlled irrigation systems reduced the amount of water applied by 32 to 70% on a silt loam soil in the temperate climate of Kansas. This is in agreement with other studies that have indicated reduced water applications with SMS-controlled compared to frequency-based irrigation on sand-based soil types, including in different turfgrass species and climates. Therefore, increased implementation of SMS-based irrigation systems could help to reduce water usage in landscapes.

Nitrate leaching was much lower in all treatments than the threshold set by the EPA for water quality. Neither irrigation (SMS- or frequency-based) nor fertilizer (rates and types) treatments had any effect on nitrate leaching, indicating leaching is negligible in fine-textured, silt loam soils in established, healthy turfgrass. Visual quality was typically best at the higher rates of nitrogen, when differences were observed.

Results from my study on a silt loam soil, which indicated negligible nitrate leaching regardless of irrigation or N fertilizer treatment, were in contrast to other studies conducted in coarse textured soils that indicated reductions in leaching with SMS irrigation and slow-release N sources. My results also differed from research done in the greenhouse on a silt loam which indicated that deeper, less frequent irrigation increased nitrate leaching compared to light, frequent irrigation. Further research is needed to compare nitrate leaching among N fertilizer types and rates, and using SMS- and frequency-based irrigation, among various soil types and climates all within one study.

References

Acclima. 2007. SC Series Controller User Manual. Acclima, Inc., Meridian, ID.

Barton, L. and T. Colmer. 2006. Irrigation and fertiliser strategies for minimising nitrogen leaching from turfgrass. Agric. Water Manage. 80:160-175.

Branham, B.E. 2008. Leaching of pesticides and nitrate in turfgrasses. p. 107-120. *In* J.B. Beard and M.P. Kenna (eds.) Water quality and quantity issues for turfgrass in urban landscapes. Council Agr. Sci. Technology, Ames, IA.

Bremer, D.J., S.J. Keeley, A. Jager, J.D. Fry and C. Lavis. 2012. In-ground irrigation systems affect lawn-watering behaviors of residential homeowners. HortTech. 22:651-658.

Burt, C., A. Clemmens, T. Strelkoff, K. Solomon, R. Bliesner, L. Hardy, T. Howell and D. Eisenhauer. 1997. Irrigation performance measures: Efficiency and uniformity. J. Irrig. Drain. Eng.-ASCE 123:423-442.

Cardenas-Lailhacar, B., M.D. Dukes and G.L. Miller. 2010. Sensor-based automation of irrigation on bermudagrass during dry weather conditions. J. Irrig. Drain. Eng. 136:184-193.

Cardenas-Lailhacar, B., M.D. Dukes and G.L. Miller. 2008. Sensor-based automation of irrigation on bermudagrass during wet weather conditions. J. Irrig. Drain. Eng. 134:120-128.

Cardenas-Lailhacar, B. and M.D. Dukes. 2012. Soil moisture sensor landscape irrigation controllers: A review of multi-study results and future implications. Transactions of the ASABE 55:581-590.

Carey, R.O., G.J. Hochmuth, C.J. Martinez, T.H. Boyer, V.D. Nair, M.D. Dukes, G.S. Toor, A.L. Shober, J.L. Cisar, L.E. Trenholm and J.B. Sartain. 2012. A review of turfgrass fertilizer management practices: Implications for urban water quality. HortTech. 22:280-291.

Chand, S., M. Ashif, M.Y. Zargar and B.M. Ayub. 2011. Nitrate pollution: A menace to human, soil, water and plant. Universal Journal of Environmental Research and Technology 1:22-32.

Cisar, J., J. Erickson, G. Snyder, J. Haydu and J. Volin. 2004. Documenting nitrogen leaching and runoff losses from urban landscapes. Environmental Impact of Fertilizer on Soil and Water 872:161-179.

Dukes, M.D. 2012. Water conservation potential of landscape irrigation smart controllers. Transactions of the ASABE 55:563-569.

Easton, Z. and A. Petrovic. 2004. Fertilizer source effect on ground and surface water quality in drainage from turfgrass. J. Environ. Qual. 33:645-655.

Engelsjord, M. and B. Singh. 1997. Effects of slow-release fertilizers on growth and on uptake and leaching of nutrients in Kentucky bluegrass turfs established on sand-based root zones. Can. J. Plant Sci. 77:433-444.

Erickson, J., J. Cisar, J. Volin and G. Snyder. 2001. Comparing nitrogen runoff and leaching between newly established St. Augustinegrass turf and an alternative residential landscape. Crop Sci. 41:1889-1895.

Erickson, J.E., D.M. Park, J.L. Cisar, G.H. Snyder and A.L. Wright. 2010. Effects of sod type, irrigation, and fertilization on nitrate-nitrogen and orthophosphate-phosphorus leaching from newly established St. Augustinegrass sod. Crop Sci. 50:1030-1036.

Frank, K.W., K.M. O’Reilly, J.R. Crum and R.N. Calhoun. 2006. The fate of nitrogen applied to a mature Kentucky bluegrass turf. Crop Sci. 46:209-215.

Geron, C., T. Danneberger, S. Traina, T. Logan and J. Street. 1993. The effects of establishment methods and fertilization practices on nitrate leaching from turfgrass. J. Environ. Qual. 22:119-125.

Grounds Maintenance. 1996. Turf acreage. Grounds Maintenance 31:10.

Guertal, E.A. and J.A. Howe. 2012. Nitrate, ammonium, and urea leaching in hybrid bermudagrass as affected by nitrogen source. Agron. J. 104:344-352.

Haley, M.B. and M.D. Dukes. 2012. Validation of landscape irrigation reduction with soil moisture sensor irrigation controllers. J. Irrig. Drain. Eng.-ASCE 138:135-144.

Hamilton, P.A., T.L. Miller and D.N. Myers. 2004. Water quality in the nation's streams and aquifers-overview of selected findings, 1991-2001. U.S. Geol. Surv. Circ.1265.

King, K.W. and J.C. Balogh. 2001. Water quality impacts associated with converting farmland and forests to turfgrass. Trans. ASAE 44:569-576.

Mangiafico, S. and K. Guillard. 2006. Fall fertilization timing effects on nitrate leaching and turfgrass color and growth. J. Environ. Qual. 35:163-171.

Mayer, P.W. and et al. 1999. Residential end uses of water. American Water Works Association Research Foundation, Denver, CO.

McCready, M.S., M.D. Dukes and G.L. Miller. 2009. Water conservation potential of smart irrigation controllers on St. Augustinegrass. Agric. Water Manage. 96:1623-1632.

Milesi, C., S.W. Running, C.D. Elvidge, J.B. Dietz, B.T. Tuttle and R.R. Nemani. 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environ. Manage. 36:426-438.

Miltner, E., B. Branham, E. Paul and P. Rieke. 1996. Leaching and mass balance of N-15-labeled urea applied to a Kentucky bluegrass turf. Crop Sci. 36:1427-1433.

Morris, K. 2003. The national turfgrass research initiative. National Turfgrass Federation and National Turfgrass Evaluation Program, Beltsville, MD.

Morton, T., A. Gold and W. Sullivan. 1988. Influence of overwatering and fertilization on nitrogen losses from home lawns. J. Environ. Qual. 17:124-130.

Pathan, S.M., L. Barton and T.D. Colmer. 2007. Evaluation of a soil moisture sensor to reduce water and nutrient leaching in turfgrass (*Cynodon dactylon* cv. wintergreen). Aust. J. Exp. Agric. 47:215-222.

Petrovic, A.M. and Z.M. Easton. 2005. The role of turfgrass management in the water quality of urban environments. International Turfgrass Society Research Journal 10:55-69.

Petrovic, A. 1990. The fate of nitrogenous fertilizers applied to turfgrass. J. Environ. Qual. 19:1-14.

Smith, V.H. 1998. Cultural eutrophication of inland, estuarine, and coastal waters. p. 7-49. *In* M.L. Pace and P.M. Groffman (eds.) Successes, limitations, and frontiers in ecosystem science. Springer-Verlag, New York, NY.

Snyder, G., B. Augustin and J. Davidson. 1984. Moisture sensor-controlled irrigation for reducing N leaching in bermudagrass turf. Agron. J. 76:964-969.

Starr, J. and H. Deroo. 1981. The fate of nitrogen-fertilizer applied to turfgrass. Crop Sci. 21:531-536.

Starrett, S.K., N.E. Christians, and T.A. Austin. 1995. Fate of nitrogen applied to turfgrass-covered soil columns. J. Irrig. Drain. Eng. 121:390-395.

Su, K., D.J. Bremer, S.J. Keeley, and J.D. Fry. 2008. Rooting characteristics and canopy responses to drought of turfgrasses including hybrid bluegrasses. Agron. J. 100:949-956.

Trenholm, L.E., J.B. Unruh, and J.B. Sartain. 2012. Nitrate leaching and turf quality in established 'Floratam' St. Augustinegrass and 'Empire' zoysiagrass. J. Environ. Qual. 41:793-9.

Trenholm, L.E., J.B. Unruh, and J.B. Sartain. 2013. Nitrate leaching and turf quality in newly sodded St. Augustinegrass. J. Plant Nutr. 36:1935-1943.

U.S. Department of Agriculture. 2006. Maryland turfgrass survey. 13 Apr. 2012: http://www.nass.usda.gov/Statistics_by_State/Maryland/Publications/Miscellaneous/turfgrass2006.pdf.

U.S. Department of Agriculture. 2004. New York turfgrass survey. 13 Apr. 2012: http://www.nysta.org/news/nystapr/2004/Turfbook04.pdf.

U.S. Environmental Protection Agency. 2012. Drinking water contaminants. http://water.epa.gov/drink/contaminants/index.cfm#2.

Vickers, A.M. 2001. Handbook of water use and conservation. WaterPlow Press, Amherst, MA.

Wu, L., R. Green, G. Klein, J. Hartin, and D. Burger. 2010. Nitrogen source and rate influence on tall fescue quality and nitrate leaching in a southern California lawn. Agron. J. 102:31-38.

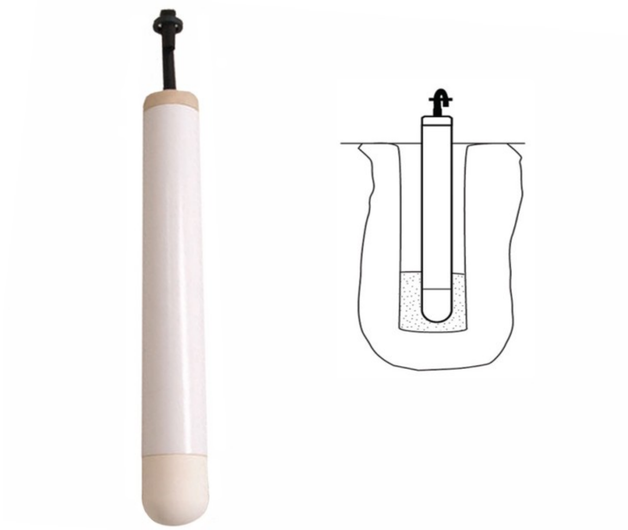

Figure 1.1 Model 1900L soil lysimeter with a porous ceramic cup at the base, Soil Moisture Equipment Corporation.

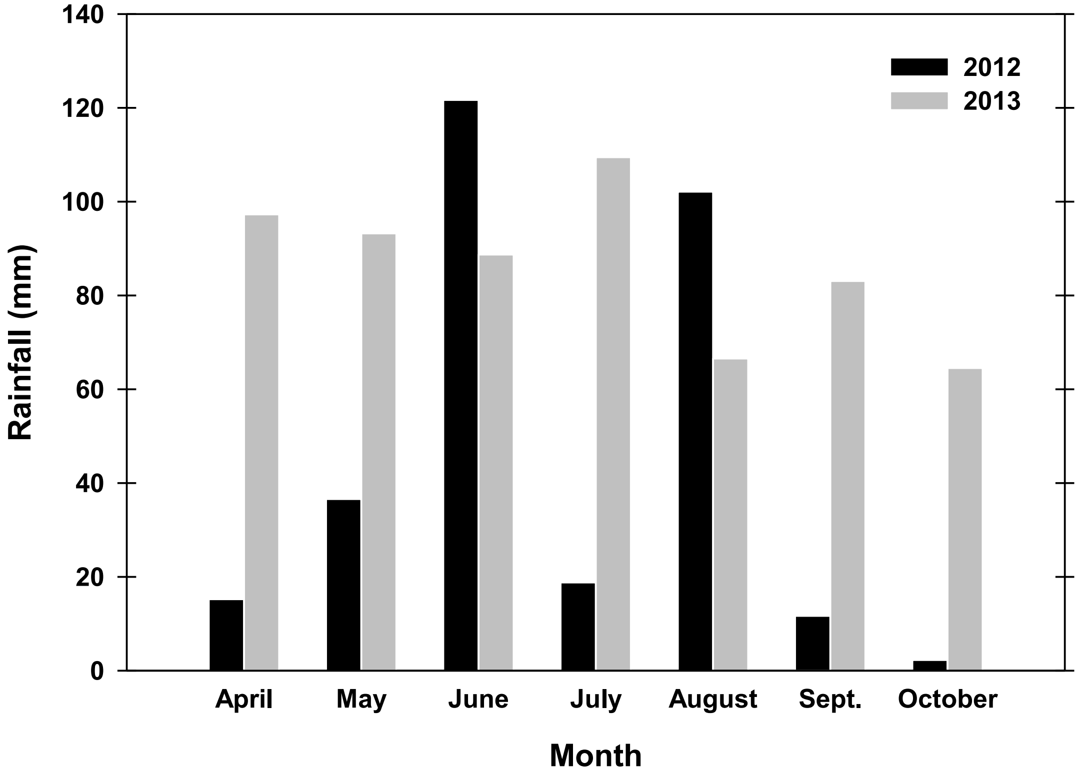

Figure 1.2 Monthly precipitation measured with the on-site weather station during the growing season in 2012 and 2013.

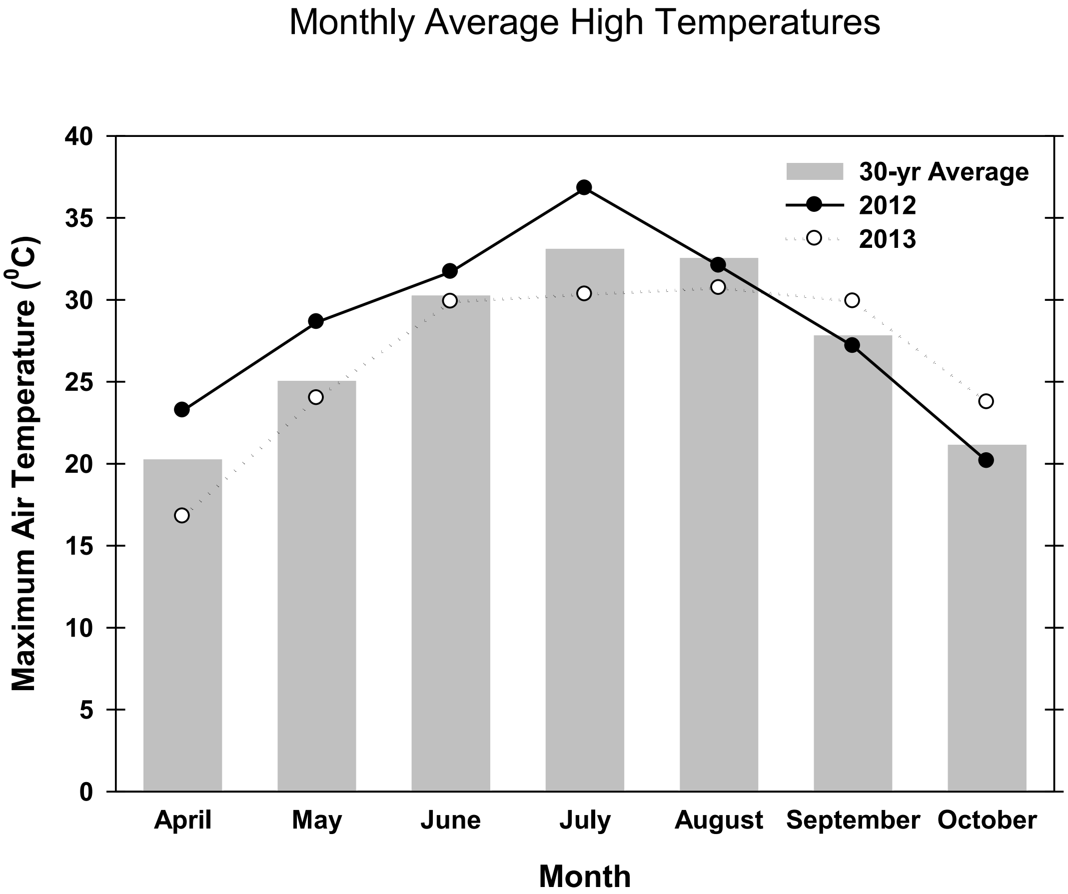

Figure 1.3 Average monthly maximum temperatures in both study years, and the 30-year averages. Data for 2012 and 2013 were obtained from the on-site weather station at the Rocky Ford Turfgrass Research Center in Manhattan, Kansas. Thirty-year averages are those reported by NOAA.

Table 1.1 Irrigation audit[†] results for treatment whole plots in 2011 and 2013.

	2011		2013	
Treatments	Net Precipitation Rate	Distribution Uniformity	Net Precipitation Rate	Distribution Uniformity
	----mm hr^{-1}----		----mm hr^{-1}----	
Frequency-based whole plot 1	25.9	0.69	26.4	0.59
Frequency-based whole plot 2	30.2	0.73	28.2	0.54
Frequency-based whole plot 3	30.0	0.79	21.8	0.58
Average	28.7	0.74	25.5	0.57
SMS-based whole plot 1	26.7	0.61	25.4	0.53
SMS-based whole plot 2	27.2	0.67	23.1	0.58
SMS-based whole plot 3	28.2	0.70	22.4	0.58
Average	27.4	0.66	23.6	0.56

[†] Audits performed following standards set by the Irrigation Association.

Table 1.2 Soil moisture sensor (SMS)-based soil water content thresholds which triggered an irrigation application in 2012 and 2013.

	Stress Thresholds	
Treatments	2012	2013
	-----------------%[†]-----------------	
SMS-based whole plot 1	23	27
SMS-based whole plot 2	25	29
SMS-based whole plot 3	22	26

[†] Percentage soil water content by volume for each SMS. Stress thresholds were increased in 2013 to improve overall turf quality ratings compared to 2012.

Table 1.3 Nitrogen rates and schedules for urea and polymer-coated urea applications in 2012 and 2013.

	Application Rates[†]	
Application Dates[‡]	122 kg N ha^{-1} yr^{-1}	244 kg N ha^{-1} yr^{-1}
	------------kg N ha^{-1}------------	
April	24.4	48.8
May	24.4	48.8
July	12.2	24.4
September	36.6	73.2
November	24.4	48.8

[†] Applications were performed based on turfgrass health at the higher rate, and the lower fertility rate was aligned to have coinciding treatments.

[‡] Applications occurred on 11 April, 30 May, 31 July, 30 September, and 22 November in 2012, and 25 April, 23 May, 11 July, 12 September, and 8 November in 2013.

Table 1.4 Yearly total irrigation values for frequency- and soil moisture sensor (SMS)-based irrigation treatments and total precipitation during the study periods.

Irrigation/Precipitation[†]	2012	2013[¶]
	---------------mm---------------	
Frequency-based	495.3a[‡]	402.0a
SMS-based	335.6b	121.1b
Difference[§]	-32%	-70%
Total Precipitation	308.3	602.8

[†] Values for the study period from 28 May to 15 October in 2012 and 27 May to 14 October in 2013.

[‡] Means followed by different letters within a column were significantly different ($P = 0.05$).

[§] (SMS – Frequency) / Frequency

[¶] In 2013, less irrigation in SMS plots was a result of greater precipitation and changes in irrigation efficiency, while less irrigation in frequency-based plots was a result of changes in irrigation efficiency and a one-week period when the irrigation system was down for maintenance.

Table 1.5 Nitrate leaching under tall fescue receiving frequency-based or soil moisture sensor-based (SMS) irrigation and urea or polymer-coated urea (PCU) in 2012.

Irrigation/Nitrogen	NO_3 Leachate[†] (mg L^{-1})				
Treatment	May[‡]	June	August	September	November
Frequency-based:					
Control	0.003[NS§]	0.053[NS]	0.003[NS]	0.103[NS]	0.220[NS]
122 kg Urea[†]	0.020	0.577	0.017	0.133	0.153
244 kg Urea	0.010	0.160	0.003	0.190	0.157
122 kg PCU	0.013	0.067	0.017	0.413	0.237
244 kg PCU	0.007	0.033	0.013	0.070	0.087
SMS-based:					
Control	0.003	0.067	0.000	0.013	0.017
122 kg Urea	0.000	0.030	0.000	0.013	0.047
244 kg Urea	0.017	0.063	0.000	0.020	0.113
122 kg PCU	0.000	0.040	0.010	0.023	0.087
244 kg PCU	0.003	0.047	0.000	0.317	0.483

[†] Suction lysimeters were installed so that the porous ceramic up at their base was at a depth of 0.76 meters and were used to extract the NO_3 leachate.

[‡] Sampling dates occurred on 8 May, 27 June, 8 August, 21 September, and 14 November.

[§] NS, means within a column were not significantly different (*P* = 0.05).

Table 1.6 Nitrate leaching under tall fescue receiving frequency-based or soil moisture sensor-based (SMS) irrigation and urea or polymer-coated urea (PCU) in 2013.

Irrigation/Nitrogen	NO_3 Leachate[†] (mg L^{-1})			
Treatment	January[‡]	April	May	August
Frequency-based:				
Control	0.190^{NS§}	0.037^{NS}	0.037^{NS}	0.010^{NS}
122 kg Urea[†]	0.117	0.040	0.063	0.067
244 kg Urea	0.100	0.033	0.023	0.003
122 kg PCU	0.170	0.040	0.057	0.023
244 kg PCU	0.063	0.020	0.067	0.033
SMS-based:				
Control	0.000	0.013	0.000	0.047
122 kg Urea	0.000	0.007	0.090	0.010
244 kg Urea	0.000	0.020	0.043	0.007
122 kg PCU	0.000	0.037	0.033	0.017
244 kg PCU	0.000	0.050	0.073	0.070

[†] Suction lysimeters were installed so that the porous ceramic cup at their base was at a depth of 0.76 meters and were used to extract the NO_3 leachate.

[‡] Sampling dates occurred on 2 January, 17 April, 31 May, and 17 August.

[§] NS, means within a column were not significantly different (*P* = 0.05).

Table 1.7 Monthly tall fescue quality for turf receiving frequency-based or soil moisture sensor-based (SMS) irrigation and urea or polymer-coated urea (PCU) in 2012.

Irrigation/Nitrogen Treatment	2012 Quality Ratings[†]							
	April[‡]	May	June	July	August	September	October	November
Frequency-based irrigation:								
Control	6.9[NS§]	6.2[NS]	5.7[NS]	5.4[NS]	6.4ab[¶]	6.7[NS]	6.6[NS]	5.3cd
Urea – Low	7.2	6.7	6.8	6.3	6.5a	6.7	6.8	6.3b
Urea – High	7.7	6.9	6.7	6.3	6.7a	6.7	7.0	7.2a
PCU – Low	7.0	6.7	6.4	6.3	6.5a	6.7	6.6	5.5c
PCU - High	7.2	7.5	7.0	7.2	6.7a	7.3	7.2	6.1b
SMS-based irrigation:								
Control	6.9	6.0	5.7	4.7	5.7d	5.7	5.7	5.1d
Urea – Low	7.2	6.3	5.8	5.0	5.3cd	5.7	6.0	6.2b
Urea – High	7.7	6.7	6.2	5.3	5.3cd	6.2	6.6	7.1a
PCU – Low	6.9	6.5	5.9	5.7	5.5c	6.0	6.0	5.2d
PCU - High	7.4	7.2	6.9	6.6	6.1b	6.3	6.3	5.2d

[†] Quality was rated on a 1 to 9 scale in which “1” represented brown, dormant or dead turfgrass and a rating of “9” represented superior quality of turfgrass in terms of color, density, and coverage.

[‡] Quality ratings are averaged among the four weekly ratings in each month, five weekly ratings in May, August, and November.

[§] NS, means within a column are not significantly different ($P = 0.05$).

[¶] Means followed by different letters within a column are significantly different ($P = 0.05$).

Table 1.8 Monthly tall fescue quality for turf receiving frequency-based or soil moisture sensor-based (SMS) irrigation and urea or polymer-coated urea (PCU) in 2013.

Irrigation/Nitrogen Treatment	2013 Quality Ratings[†]					
	May[‡]	June	July	August	September	October
Frequency-based irrigation:						
Control	5.1[NS§]	5.7d[¶]	5.7e	6.3[NS]	6.8[NS]	6.0[NS]
Urea – Low	5.9	6.0cd	6.2cd	6.9	7.0	7.0
Urea – High	6.8	7.0b	7.2b	7.1	7.3	8.0
PCU – Low	5.5	6.3d	6.2cd	7.1	6.8	6.3
PCU - High	6.2	7.0b	8.0a	7.4	7.0	7.0
SMS-based irrigation:						
Control	5.1	5.0e	5.0f	6.3	6.6	6.3
Urea – Low	5.7	6.0cd	5.8de	6.7	6.8	7.0
Urea – High	6.8	7.0b	7.3b	7.0	6.7	7.7
PCU – Low	5.3	6.1cd	6.3c	7.0	6.6	6.3
PCU - High	6.3	7.5a	8.0a	7.3	6.7	6.7

[†] Quality was rated on a 1 to 9 scale in which “1” represented brown, dormant or dead turfgrass and a rating of “9” represented superior quality of turfgrass in terms of color, density, and coverage.

[‡] Quality ratings are averaged among the four weekly ratings in each month, five weekly ratings in May, and August.

[§] NS, means in a column are not significantly different ($P = 0.05$).

[¶] Means followed by different letters within a column are significantly different ($P = 0.05$).

Chapter 2 - Effects of Irrigation, Cutting Height, and Trinexapac-Ethyl on Mowing Requirements of Tall Fescue

Abstract

Mowing requirements can be affected by irrigation strategy, cutting height, and plant growth regulators, but information is limited on how they may interact. The objectives of this research were to evaluate irrigation strategy, cutting height, and trinexapac-ethyl [TE, ethyl 4-(cyclopropylhydroxymethylene)-3,5-dioxocyclohexanecarboxylate] for their influence on irrigation and mowing requirements. Tall fescue [*Festuca arundinacea*] was irrigated: 1) three times weekly without regard to precipitation (frequency-based); or 2) after soil under turf reached a predetermined water content threshold between 26 and 29% (soil moisture sensor-based irrigation, SMS). Four sub-plots included mowing at 5.1 cm or 8.9 cm, based upon the 1/3 rule, with or without monthly applications of TE. Using SMS to guide irrigation resulted in water savings of 32 to 70%, but irrigation strategy did not influence total mowings. In 2012, tall fescue mowed at 5.1 cm and treated with TE required three fewer mowings than untreated turf mowed at 5.1 cm; at 8.9 cm cutting height, only one fewer mowing resulted after TE application. Mowing at 8.9 vs. 5.1 cm, or using TE vs. untreated resulted in a 9% reduction in total mowings required in 2013. Applications of TE are more beneficial in turfgrass maintained at lower mowing heights.

Introduction

Supplies of fresh water and fuel are becoming increasingly important as the global population rises. Urbanization has led to an increase in turfgrass coverage (Morris, 2003), and 50 to 80% of all turf is used in residential landscapes (Grounds Maintenance, 1996; U.S. Department of Agriculture (USDA), 2004, 2006). With turfgrass covering 16 to 20 million hectares in the USA, it is now an area three times larger than any other irrigated crop (USDA, 2004, 2006; Milesi et al., 2005). Furthermore, residential and commercial turfgrass mowers consume over 4.5 billion liters of gasoline in the USA annually to maintain these areas (U.S. Department of Energy, 2010).

A survey conducted by Bremer et al. (2012), found that residential homeowners with in-ground irrigation systems watered more frequently and routinely than homeowners without in-ground irrigation systems. Furthermore, an improperly adjusted in-ground irrigation system can apply a much higher amount of water than a manual irrigation system on a per area basis (Mayer et al., 1999; Vickers, 2001).

Advances in irrigation technology have provided high quality soil moisture sensors (SMS) that, when properly installed and calibrated, accurately measure the soil water content within a given area. Attaching SMS to a controller makes the controller “smart.” A “smart” controller simply refers to the system’s ability to adjust irrigation amounts and frequency based on weather conditions, rainfall, and evapotranspiration of the area being monitored. Sensors can then be assigned to individual or multiple irrigation zones, which are then attached to a central controller. Typically, the controller will display soil water content as a percentage for each SMS. Through observation of the occurrence of wilt stress to the turfgrass and the corresponding soil water content displayed by the controller, a threshold level can then be set for the SMS. This threshold can be set to represent any level of visual stress that the plant is undergoing, or a value higher than the level at which stress occurs, to maintain a desired turfgrass or plant quality. As the soil water content drops below this threshold, the controller will trigger an irrigation cycle to occur, or bypass an irrigation cycle altogether if soil water content remains above the threshold level set for that area. Proper installation of SMS is important, as their placement in a non-representative (overly dry or wet) area may result in no irrigation savings or never allowing a system to run (Dukes, 2012). For example, SMS installed in a very low area of a turfgrass stand which remains wet through most of the year can cause the remaining turfgrass to rarely or never receive irrigation, which will eventually lead to death.

Bremer et al. (2012) reported that 16% to 24% of homeowners with in-ground irrigation systems never adjusted their controllers. In such situations, a “Smart” controller with properly adjusted SMSs could improve irrigation efficiency and save water (Cardenas-Lailhacar and Dukes, 2010). In Florida (Cardenas-Lailhacar et al., 2008), SMS systems saved up to 88% more water than systems equipped with only a rain shutoff sensor, with no significant differences in common bermudagrass [*Cynodon dactylon*] quality. Those authors also reported that irrigation water savings, when averaged across all four SMS-based systems used, were 72% compared to traditional timer-based irrigation controllers during wet conditions (Cardenas-Lailhacar et al., 2008). Cardenas-Lailhacar et al. (2010) also observed an average water savings of 34% when using the same SMS systems compared to traditional timer-based irrigation practices, during dry conditions. At homes in southwestern Florida, a configured SMS system with only one sensor installed to control the system saved 65% compared to the water used by traditional timer-based irrigation practices (Haley and Dukes, 2012).

Irrigation has a direct effect on turfgrass growth. When irrigated twice weekly at 80% ET, tall fescue growing on a sandy loam in southern California had higher visual quality ratings than plots irrigated four times weekly at 80% ET (Richie et al., 2002). When irrigation frequency was reduced from 2 to 3 times weekly to every two weeks, clipping yields were reduced up to 35% and tall fescue growth and water consumption were reduced by 34% (Biran et al., 1981). Reducing irrigation amount from 100% of ET to 60% of ET resulted in a 0.6 mm d^{-1} reduction in tall fescue vertical growth rate (Fu et al., 2007).

Mowing height also influences tall fescue growth habits. Increasing the mowing height from 3 to 6 cm increased the relative average water consumption and dry matter production of tall fescue by 29% (Biran et al., 1981). By following the standard one-third rule of mowing, frequency increases as mowing height declines (Christians, 2004). Removing more than one-third of the turfgrass canopy at one time can result in added stress to the turfgrass, and in some extreme situations scalping which gives the turfgrass a bleached appearance and negatively impacts visual quality (Fry and Huang, 2004).

Plant growth regulators (PGR) have been used to reduce vertical extension rates and mowing requirements in cool-season grasses. In central Italy, two applications of trinexapac-ethyl reduced clipping yields Kentucky bluegrass and tall fescue by 40% and 33%, respectively (Pannacci et al., 2004). Kentucky bluegrass at the Tangshan Nanhu International Golf Club, Hebei Province, China that was treated with trinexapac-ethyl every 10 d exhibited a reduction in clipping yields by up to 45% (Wang et al. 2009).

To my knowledge, no research has investigated the effects of irrigation management, mowing height, and plant growth regulator use simultaneously on tall fescue. As such, my objectives were to evaluate irrigation management, mowing height, and trinexapac-ethyl for their influence on mowing and associated fuel and labor requirements on a tall fescue lawn.

Materials and Methods

The experiment was conducted on a well-established sward of unknown turf-type tall fescue cultivars at the Rocky Ford Turfgrass Research Center in Manhattan, Kansas (39^{o}13’53” N, 96^{o}34’51” W). Soil was a Chase silt loam (fine, montmorillonitic, mesic, Aquic, Arguidoll) with a pH of 7.4, a P level of 60 mg kg^{-1}, and a K level of 478 mg kg^{-1}.

The study ran from 9 April to 30 Nov. 2012 and 13 May to 22 Oct. 2013. Turf received a total N level of 195 kg ha^{-1} yr^{-1} from applications of polymer-coated urea (41N-0P-0K) at 49 kg ha^{-1} on 11 April 2012 and 13 May 2013; 24 kg ha^{-1} on 27 June 2012 and 3 July 2013; 73 kg ha^{-1} on 30 Sept. 2012 and 13 Sept. 2013; and 49 kg ha^{-1} on 8 Nov. 2012 and 22 Oct. 2013.

Experimental design was a split-plot with irrigation treatment as the whole plot factor and mowing height/trinexapac-ethyl treatment and mowing height as the subplots. Whole plot irrigation treatments included: 1) irrigation applied for 15 minutes three days weekly to mimic a typical homeowner’s frequency-based schedule (hereafter referred to as frequency-based irrigation); and 2) irrigation applied when triggered by a predetermined soil water content (hereafter referred to as SMS-based irrigation).

Each of six whole plot irrigation treatments measuring 27 m by 9 m was watered with eight Hunter I-20 rotary irrigation heads (Hunter Industries, San Marcos, CA, USA). Four heads were located on the sides of each whole plot (180 degree rotation) and the remaining four were in the corners (90 degree rotation). Three of the whole plots were irrigated three times weekly for fifteen minutes, regardless of precipitation or prevailing weather conditions, to mimic the approach a homeowner who has little knowledge of irrigation might use (frequency irrigation).

Irrigation frequency and time were governed by a Hunter Pro-C controller (Hunter Industries, San Marcos, CA, USA).

Irrigation audits were performed in 2011 (prior to the start of the experiment) and 2013 to evaluate net irrigation rates and distribution uniformity (Table 1.1) based on standards set by the Irrigation Association (Irrigation Association (IA), Falls Church, VA, USA). The calculated distribution uniformity in 2011 for frequency-based whole plots ranged from 0.69 to 0.79, and for sensor-based whole plots it ranged from 0.61 to 0.70. The calculated distribution uniformity in 2013 for non-sensor whole plots ranged from 0.54 to 0.59, and for sensor-based whole plots it ranged from 0.53 to 0.58. The calculated net precipitation rate in 2011 for frequency-based whole plots ranged from 25.9 mm hr^{-1} to 30.2 mm hr^{-1}, and for sensor-based whole plots it ranged from 26.7 mm hr^{-1} to 28.2 mm hr^{-1}. The calculated net precipitation rate in 2013 for frequency-based whole plots ranged from 21.8 mm hr^{-1} to 28.2 mm hr^{-1}, and for sensor-based whole plots it ranged from 22.4 mm hr^{-1} to 25.4 mm hr^{-1}. Whole plot irrigation treatments which were irrigated based on the three-day-a-week homeowner frequency received an average of 18 to 22 mm per week in 2012 based upon the 2011 IA audit and 16 to 21 mm per week in 2013 based upon the 2013 IA audit.

In three of the six whole plots, irrigation was controlled by soil moisture sensors attached to an automated controller (Acclima SC6, Acclima, Inc., Meridian, ID, USA) (SMS-based irrigation). One soil moisture sensor (Digital time domain transmissometry, Model ACC-SEN-TDT, Acclima, Inc., Meridian, ID, USA) was installed in each of the three whole plots managed by this controller. Each sensor was buried near the center of each whole plot at a depth of 7.0 cm. Following the manufacturer's protocol, "field capacity" was determined for each sensor as a percentage by volume (Acclima, 2007).

Stress thresholds for the tall fescue were determined for each whole plot replicate. Three separate irrigation events, in which 9 mm of water was applied, were followed by a dry down period. Stress was defined as a blue-gray appearance to turf in that whole plot, and associated leaf rolling indicating occurrence of wilt. The percentage soil water content corresponding to stress was recorded, and the average of all three observations was used to determine the threshold for each zone. The initial average stress threshold of SMS-based whole plots was set at 23%. Due to lower quality ratings in SMS-based than in frequency-based treatments in 2012, thresholds were increased to 27% in all three SMS plots to reduce stress occurrence and improve quality ratings in 2013. When soil moisture dropped below the threshold, the system applied enough irrigation to provide at least 25.4 mm of water across all areas of the whole plots.

Four mowing height/trinexapac-ethyl subplots, each measuring 1.8 m by 4.6 m, were located within each whole plot irrigation treatment. Treatments were: 1) mowing at 5.1 cm; 2) mowing at 8.9 cm; 3) mowing at 5.1 cm in conjunction with trinexapac-ethyl [ethyl 4-(cyclopropylhydroxymethylene)-3,5-dioxocyclohexanecarboxylate] application; and 4) mowing at 8.9 cm in conjunction with trinexapac-ethyl application.

Mowing was done with a Poulan Pro rotary mower (Poulan Pro RP412211, Charlotte, NC, USA). Three canopy height measurements were taken in each sub plot three days weekly during the study to determine when mowing was required based upon the 1/3 rule. These measurements where performed visually with the use of a metric ruler. When the average height of subplots within the 5.1 cm mowing treatments had reached 7.7 cm, mowing was done. Likewise, when the average height of subplots within the 8.9 cm mowing height had reached 13.4 cm, those plots were mowed. Trinexapac ethyl was applied monthly at 0.3 kg a.i. ha^{-1} using a Gregson-Clark Spreader-Mate Model B sprayer (Gregson-Clark Spraying Equipment, Caledonia, NY, USA) installed in a Lesco commercial spreader with a four nozzle folding boom. Nozzles were TeeJet AI8006VS (TeeJet Technologies, Wheaton, IL, USA). Applications in 2012 occurred on 16 April, 19 May, 18 June, 12 July, 10 August, 5 September, and 3 October. Applications in 2013 occurred on 15 May, 17 June, 17 July, 16 August, 19 September, and 18 October.

Data were collected on total applied water, number of mowings, and estimated fuel and labor hours required. Total water applied was determined as described in Chapter 1. Each time a treatment required mowing, it was recorded. Fuel used was determined based upon a pre-study evaluation of fuel consumed by the engine on this mower. The mower's engine was a Briggs and Stratton 600 series with 190 cm^3 and 8.13 N m of gross torque (Briggs and Stratton, Milwaukee, WI, USA). To determine average fuel usage, a 93 m^2 area was defined. Mowing was done over this area three separate times to determine an average walking speed of 2.6 km hr^{-1} and a cutting time of 251 s. Similarly, fuel usage was determined for three distinct mowing events over the area. Fuel used was determined by starting with a full tank and measuring the amount of fuel required to return the tank to full after mowing. Average fuel usage was determined to be 51 mL of 87 percent octane unleaded gasoline. Using this baseline information, individual subplots required 22.6 s (7.6 hr ha^{-1}) of labor and 4.6 mL (5.5 L ha^{-1}) of gasoline to mow. These coefficients were used with mowing frequency to determine differences in fuel usage and labor hours among treatments.

Turfgrass quality was rated weekly on a scale of 1 to 9, on which 1 = brown, dormant or dead turfgrass, and a rating of 9 = optimum color, density, and uniformity (Skogley and Sawyer, 1992). A rating of 5 was considered the minimum acceptable turfgrass quality for a home lawn. Weekly quality ratings were averaged for each month.

Data were subjected to analysis of variance using PROC GLIMMIX in Statistical Analysis System (SAS Institute Inc., Cary, NC, USA), and means were separated using Fisher's Protected LSD at $P < 0.05$.

Results and Discussion

During the dry year of 2012 and the wet year of 2013, irrigation water savings from sensor-based treatments totaled 32% and 70%, respectively. Chapter 1 provides an in-depth discussion of these results (pages 12 to 13).

Regarding total mowings and accompanying labor requirements and fuel usage, irrigation never had an effect (Table 2.1). This was likely due to the good soil quality at the site, and because tall fescue did not experience severe stress before water was applied. Tall fescue is deep rooted (Su et al., 2008) and may have been able to extract water from deep in the soil and maintain growth even up to the point where wilt was first observed. In 2013, rainfall was abundant (Fig. 1.2) and this likely also contributed to the lack of differences between the irrigation treatments.

Mowing height (2013) and TE (2012 and 2013) main effects were significant for total mowings, as was the TE x Mowing interaction (2012) (Table 2.1). An interaction was seen in 2012, possibly because of higher than average temperatures and relatively low precipitation, which resulted in stressful growing conditions for the turfgrass subplots. An interaction did not occur in 2013. Mild temperatures and abundant rainfall provided optimal growing conditions, which may have minimized the effects of TE on turfgrass mown at either 5.1 or 8.9 cm. As such, data will be discussed for the TE x Mowing interaction in 2012 and mowing height and TE main effects in 2013. In 2012, tall fescue mowed at 5.1 cm and treated with TE required three fewer mowings than untreated turf mowed at 5.1 cm (Table 2.2). However, at 8.9 cm, only one fewer mowing resulted after TE application. In subplots not treated with TE and mowed at 8.9 vs. 5.1 cm, a reduction in mowing resulted in labor savings of 11.3 hr ha^{-1} and a fuel savings of

8.2 L ha^{-1} for tall fescue. Tall fescue mowed at 8.9 cm required 7.6 hr ha^{-1} less labor and 5.5 L ha^{-1} less fuel when treated with TE, and when mowed at 5.1 cm it required 22.7 hr ha^{-1} less labor and 16.5 L ha^{-1} less fuel when treated with TE.

In 2013, turf mowed at 5.1 cm required more total mowings (14.5) than that mowed at 8.9 cm (13.2) (Table 2.3). Similarly, turf treated with TE in 2013 also required an average of 13.2 mowings, which was lower than that not treated (14.5) (Table 2.4). In general, turf at lower mowing heights requires more mowing when using the one-third rule as a guide, and that was the case herein despite the use of TE.

In 2013, mowing at 8.9 rather than 5.1 cm or applying TE rather than not, resulted in the same labor (9.9 hr ha^{-1}) and fuel savings (7.4 L ha^{-1}) (Tables 2.3 and 2.4).

Tall fescue mowed at 7 cm on a Cecil sandy clay loam, and treated with TE at 0.4 kg a.i. ha^{-1} required one to three fewer mowings within a 5 to 7 week period after treatment in Georgia compared to untreated turf (Johnson, 1993). Trinexapac-ethyl applied at 0.375 kg a.i. ha^{-1} month^{-1} reduced clipping dry weights by 33% in tall fescue beginning after the second application in central Italy (Pannacci, 2004). On Kentucky bluegrass, TE applied at 0.625 kg ha^{-1} every 10 days reduced canopy height from 41 to 47% and reduced clipping yields at the Tangshan Nanhu International Golf Club, Hebei Province, China (Wang et. al., 2009).

Turf Quality

A significant interaction between irrigation strategy and mowing/TE occurred in June 2012 and again in September 2013 (Table 2.5). In June 2012, tall fescue receiving the frequency-based schedule had higher quality than SMS-based irrigated turf (Table 2.6). This was caused, in part, by stress thresholds for the SMS-based irrigation being set too low in 2012, and was corrected in 2013. In addition, turf mowed at 5.1 cm and receiving TE, or 8.9 cm without TE, had higher quality than the other treatments in plots receiving frequency-based irrigation.

In September 2013, tall fescue irrigated by a frequency-based schedule, mowed at 5.1 cm and not receiving TE had lower quality than other treatments receiving frequency-based irrigation (Table 2.7). The over-application of water by frequency-based treatments in combination with the precipitation of 2013 may have helped to maintain quality in the plots treated with TE. Within tall fescue irrigated based upon SMS, TE application resulted in lower quality at both the 5.1 and 8.9 cm heights. With irrigation occurring only as needed by the SMS-based treatments, a slight reduction in quality was observed within the TE-treated plots. Tall fescue treated once with TE at 0.4 or 0.8 kg a.i. ha^{-1} also exhibited a reduction in quality up to seven weeks after treatment between 1990 and 1993 in Georgia (Johnson, 1993).

Conclusions

Irrigation treatment had no effect on total mowings and associated requirements for labor and fuel under the conditions of this experiment. Trinexapac-ethyl was more effective at reducing total mowings on lower-mowed turf in one year of the experiment. In the second year of the study, mowing higher (8.9 vs. 5.1 cm) resulted in a similar reduction in mowing requirements as applying TE. Turfgrass maintained at higher cutting heights helps to reduce mowing frequency and does not benefit from applications of TE as much as turfgrass maintained at lower cutting heights. Applications of TE could help to reduce the number of mowings and consequently, reduce labor and fuel usage in situations where turfgrass needs to be maintained at lower cutting heights.

References

Acclima. 2007. SC Series Controller User Manual. Acclima, Inc., Meridian, ID.

Biran, I., B. Bravdo, I. Bushkinharav and E. Rawitz. 1981. Water-consumption and growth-rate of 11 turfgrasses as affected by mowing height, irrigation frequency, and soil-moisture. Agron. J. 73:85-90.

Bremer, D.J., S.J. Keeley, A. Jager, J.D. Fry and C. Lavis. 2012. In-ground irrigation systems affect lawn-watering behaviors of residential homeowners. Horttechnology 22:651-658.

Cardenas-Lailhacar, B., M.D. Dukes and G.L. Miller. 2010. Sensor-based automation of irrigation on bermudagrass during dry weather conditions. J. Irrig. Drain Eng. 136:184.

Cardenas-Lailhacar, B., M.D. Dukes and G.L. Miller. 2008. Sensor-based automation of irrigation on bermudagrass during wet weather conditions. J. Irrig. Drain Eng. 134:120.

Cardenas-Lailhacar, B. and M.D. Dukes. 2012. Soil moisture sensor landscape irrigation controllers: A review of multi-study results and future implications. Transactions of the ASABE 55:581-590.

Christians, N.E. 2004. Fundamentals of turfgrass management. John Wiley & Sons, Inc., Hoboken, N.J.

Dukes, M.D. 2012. Water conservation potential of landscape irrigation smart controllers. Transactions of the ASABE 55:563-569.

Fry, J. and B. Huang. 2004. Applied turfgrass science and physiology. John Wiley & Sons, Inc., Hoboken, N.J.

Fu, J., J. Fry and B. Huang. 2007. Growth and carbon metabolism of tall fescue and zoysiagrass as affected by deficit irrigation. Hortscience 42:378-381.

Grounds Maintenance. 1996. Turf acreage. Grounds Maintenance 31:10.

Haley, M.B. and M.D. Dukes. 2012. Validation of landscape irrigation reduction with soil moisture sensor irrigation controllers. Journal of Irrigation and Drainage Engineering-ASCE 138:135-144.

Johnson, B.J. 1993. Response of tall fescue to plant growth regulators and mowing frequencies. J. Environ. Horticulture 11:163-167.

Mayer, P.W., et al. 1999. Residential end uses of water. American Water Works Association Research Foundation, Denver, CO.

Milesi, C., S. Running, C. Elvidge, J. Dietz, B. Tuttle and R. Nemani. 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environ. Manage. 36:426-438.

Morris, K. 2003. The national turfgrass research initiative. National Turfgrass Federation and National Turfgrass Evaluation Program, Beltsville, MD.

Pannacci, E., G. Covarelli and F. Tei. 2004. Evaluation of trinexapac-ethyl for growth regulation of five cool-season turfgrass species. Acta Horticulturae 349-351.

Richie, W., R. Green, G. Klein and J. Hartin. 2002. Tall fescue performance influenced by irrigation scheduling, cultivar, and mowing height. Crop Sci. 42:2011-2017.

Skogley, C.R. and C.D. Sawyer. 1992. Field research. p. 589-614. *In* D.V. Waddington, R.N. Carrow, and R.C. Shearman (ed.) Turfgrass. Agronomy Monograph 32 ed. ASA/CSSA/SSSA, Madison, Wis.

Su, K., D.J. Bremer, S.J. Keeley, and J.D. Fry. 2008. Rooting characteristics and canopy responses to drought of turfgrasses including hybrid bluegrasses. Agron. J. 100:949-956.

U.S. Department of Agriculture. 2006. Maryland turfgrass survey. 13 Apr. 2012:http://www.nass.usda.gov/Statistics_by_State/Maryland/Publications/Miscellaneous/turfgrass2006.pdf.

U.S. Department of Agriculture. 2004. New York turfgrass survey. 13 Apr. 2012:http://www.nysta.org/news/nystapr/2004/Turfbook04.pdf.

U.S. Department of Energy. 2011. Clean cities guide to alternative fuel commercial lawn equipment. http://www.nrel.gov/docs/fy12osti/52423.pdf.

Vickers, A.M. 2001. Handbook of water use and conservation. WaterPlow Press, Amherst, MA.

Wang, X., T. Hu, Q. Wang, L. Tian, X. Zhang and K. Tian. 2009. Growth of Kentucky bluegrass as influenced by nitrogen and trinexapac-ethyl. Agric. Sci. China 8:1498-1502.

Table 2.1 *P* values from the analysis of variance for main effects of irrigation (IRR), trinexapac-ethyl (TE), mowing height, and their interactions on total mowings on tall fescue in Manhattan, KS in 2012 and 2013.

Effect	2012	2013
	-----------------*P* value-----------------	
Irrigation (IRR)	0.5473	1.0000
Trinexapac-ethyl (TE)	0.0001	0.0006
Mowing height	0.1249	0.0006
TE*IRR	0.8176	0.2707
IRR*Mowing height	0.1249	1.0000
TE*Mowing height	0.0235	0.2707
TE*IRR*Mowing height	0.2614	0.2707

Table 2.2 Interaction between mowing height and trinexapac-ethyl on total mowings and labor and fuel requirements for tall fescue between 9 April and 30 November in Manhattan, KS in 2012.

Mowing Height (cm)	Trinexapac-ethyl[†]	Total mowings[‡]	Labor (hr ha^{-1})[§]	Fuel usage (L ha^{-1})[¶]
5.1	No	9.0a[#]	68.2	49.5
5.1	Yes	6.0c	45.5	33.0
8.9	No	7.5b	56.9	41.3
8.9	Yes	6.5c	49.3	35.8

[†] Trinexapac-ethyl was applied at 0.3 kg a.i. ha^{-1} on 16 April, 19 May, 18 June, 12 July, 10 August, 5 September, and 3 October in 2012.

[‡] Mowing was done following the one-third rule: turf at 5.1 cm was mowed when it reached 7.6 cm; turf at 8.9 cm was mowed when it reached 13.3 cm.

[§] Labor was determined by multiplying total mowing by 7.6 hr ha^{-1}.

[¶] Fuel usage was determined by multiplying total mowing by 5.5 L ha^{-1}.

[#] Means followed by different letters within a column are significantly different ($P = 0.05$).

Table 2.3 Effect of mowing height on total number of mowings, and labor and fuel requirements for tall fescue between 13 May and 22 October in Manhattan, KS in 2013.

Mowing Height (cm)	Total mowings[†]	Labor (hr ha^{-1})[‡]	Fuel usage (L ha^{-1})[§]
5.1	14.5a[¶]	110.0	79.8
8.9	13.2b	100.1	72.4

[†] Mowing was done following the one-third rule: turf at 5.1 cm was mowed when it reached 7.6 cm; turf at 8.9 cm was mowed when it reached 13.3 cm.

[‡] Labor was determined by multiplying total mowing by 7.6 hr ha^{-1}.

[§] Fuel usage was determined by multiplying total mowing by 5.5 L ha^{-1}.

[¶] Means followed by different letters within a column are significantly different (*P* = 0.05).

Table 2.4 Effect of trinexapac-ethyl application on total number of mowings, and labor and fuel requirements for tall fescue between 13 May and 22 October in Manhattan, KS in 2013.

Treatment	Total mowings[†]	Labor (hr ha^{-1})[‡]	Fuel Usage (L ha^{-1})[§]
Untreated	14.5a[¶]	110.0	79.8
Trinexapac-ethyl	13.2b	100.1	72.4

[†] Mowing was done following the one-third rule: turf at 5.1 cm was mowed when it reached 7.6 cm; turf at 8.9 cm was mowed when it reached 13.3 cm.

[‡] Labor was determined by multiplying total mowing by 7.6 hr ha^{-1}.

[§] Fuel usage was determined by multiplying total mowing by 5.5 L ha^{-1}.

[¶] Means followed by different letters within a column are significantly different (*P* = 0.05).

Table 2.5 Monthly *P* values from analysis of variance for the irrigation x mowing/trinexapac-ethyl interaction in 2012 and 2013.

Month	2012	2013
	-----------------*P* value-----------------	
April	0.3349	------[†]
May	0.8883	0.9978
June	0.0355	0.3274
July	0.4294	1.0000
August	0.1554	0.4162
September	0.6615	0.0002
October	0.4011	0.1409
November	0.2072	------[†]

[†] No data were collected in April or November 2013.

Table 2.6 Effect of irrigation strategy[†], mowing height[‡], and trinexapac-ethyl[§] on tall fescue quality[¶] in 2012.

		April[#]	May	June	July	Aug.	Sept.	Oct.	Nov.
Frequency-based irrigation	Trinexapac -ethyl								
5.1 cm	No	7.0[NS††]	6.9[NS]	6.7b[‡‡]	6.0[NS]	6.3[NS]	6.9[NS]	6.8[NS]	6.7[NS]
5.1 cm	Yes	6.6	6.9	7.0a	5.8	6.7	6.8	7.0	6.5
8.9 cm	No	7.4	6.9	7.0a	6.4	6.3	6.8	6.8	5.9
8.9 cm	Yes	7.2	6.7	6.7b	6.1	6.3	6.7	6.3	5.1
SMS-based irrigation									
5.1 cm	No	6.8	6.5	6.0c	5.8	5.5	6.2	6.5	6.4
5.1 cm	Yes	6.8	6.5	6.0c	5.7	5.7	5.9	6.3	6.1
8.9 cm	No	7.2	6.7	6.1c	5.8	5.3	6.3	6.2	6.0
8.9 cm	Yes	7.0	6.4	6.0c	5.8	5.7	5.9	6.0	4.9

[†] Irrigation was done on a frequency-based schedule (three times weekly for 15 minutes) or after a predetermined soil water content threshold had been reached (SMS-based irrigation).

[‡] Mowing was done as needed following the 1/3 rule to return the canopy to the prescribed height.

[§] Trinexapac-ethyl was applied at 0.3 kg a.i. ha^{-1} on 16 April, 19 May, 18 June, 12 July, 10 August, 5 September, and 3 October in 2012.

[¶] Quality was rated on a 1 to 9 scale in which “1” represented brown, dormant or dead turfgrass and a rating of “9” represented superior quality of turfgrass in terms of color, density, and coverage.

[#] Average monthly quality ratings were based on the four weekly ratings in each month, five for May, August and November.

[††] NS, means within a column are not significantly different (*P* = 0.05).

[‡‡] Means followed by different letters within a column are significantly different (*P* = 0.05).

Table 2.7 Effect of irrigation strategy[†], mowing height[‡], and trinexapac-ethyl[§] on tall fescue quality[¶] in 2013.

		May[#]	June	July	Aug.	Sept.	Oct.
Frequency-based irrigation	Trinexapac-ethyl						
5.1 cm	No	6.2[NS††]	7.0[NS]	7.0[NS]	6.9[NS]	6.7bc[‡‡]	7.0[NS]
5.1 cm	Yes	6.2	7.0	7.0	7.2	7.0a	7.0
8.9 cm	No	6.2	7.0	7.0	7.4	7.0a	7.0
8.9 cm	Yes	6.2	7.0	7.0	7.4	7.0a	7.0
SMS-based irrigation							
5.1 cm	No	6.2	7.0	6.8	6.7	6.8abc	6.3
5.1 cm	Yes	6.2	7.0	6.8	6.8	6.3d	6.3
8.9 cm	No	6.2	7.0	6.8	6.9	7.0ab	7.0
8.9 cm	Yes	6.1	6.8	6.8	6.9	6.7c	6.7

[†] Irrigation was done on a frequency-based schedule (three times weekly for 15 minutes) or after a predetermined soil water content threshold had been reached (SMS-based irrigation).

[‡] Mowing was done as needed following the 1/3 rule to return the canopy to the prescribed height.

[§] Trinexapac-ethyl was applied at 0.3 kg a.i. ha^{-1} on 16 April, 19 May, 18 June, 12 July, 10 August, 5 September, and 3 October in 2012.

[¶] Quality was rated on a 1 to 9 scale in which “1” represented brown, dormant or dead turfgrass and a rating of “9” represented superior quality of turfgrass in terms of color, density, and coverage.

[#] Average monthly quality ratings were based on the four weekly ratings in each month, five for May and August.

[††] NS, means within a column are not significantly different (*P* = 0.05).

[‡‡] Means followed by different letters within a column are significantly different (*P* = 0.05).